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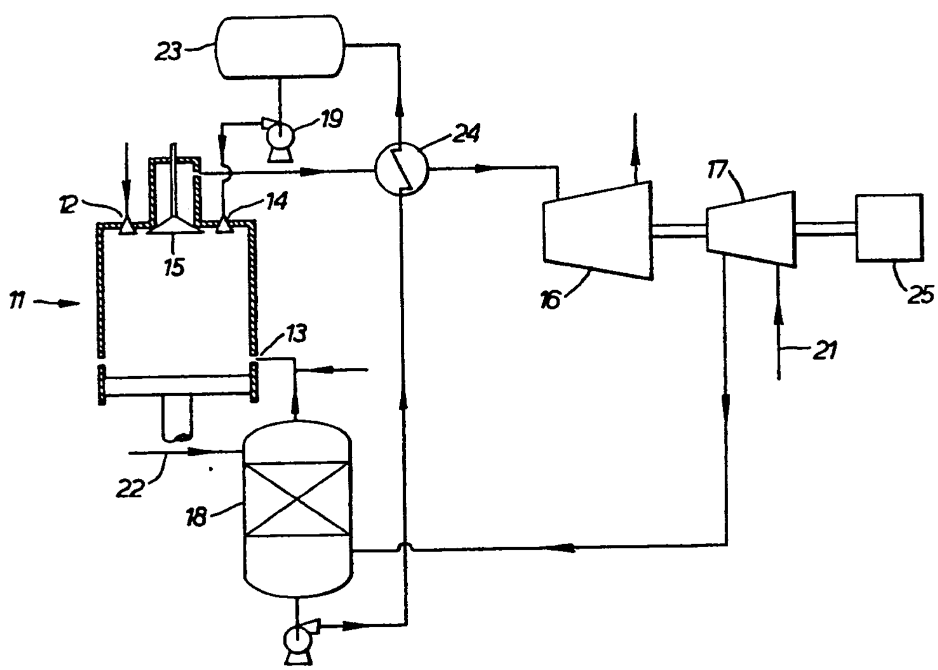
(58) Field of search
F1B

(54) I.C. engine with water injection

(57) Water is injected into the combustion chamber through a valve 14 during the compression stroke and the combustion/expansion stroke but not during injection of fuel through a valve 12. The amount of excess air introduced is reduced by an amount corresponding to the cooling effect of the water injection. The exhaust gas drives a turbine 16 which drives a compressor 17 which in turn compresses the air. The water is heated by heat exchange with the exhaust gas in a heat exchanger 24 and the compressed air in a contact heat exchanger 18. Values of water injection temperature and relative quantities of fuel and water, engine compression ratio, intake air compression pressures and excess air ratios are disclosed.



The drawing originally filed was informal and the print here reproduced is taken from a later filed formal copy.

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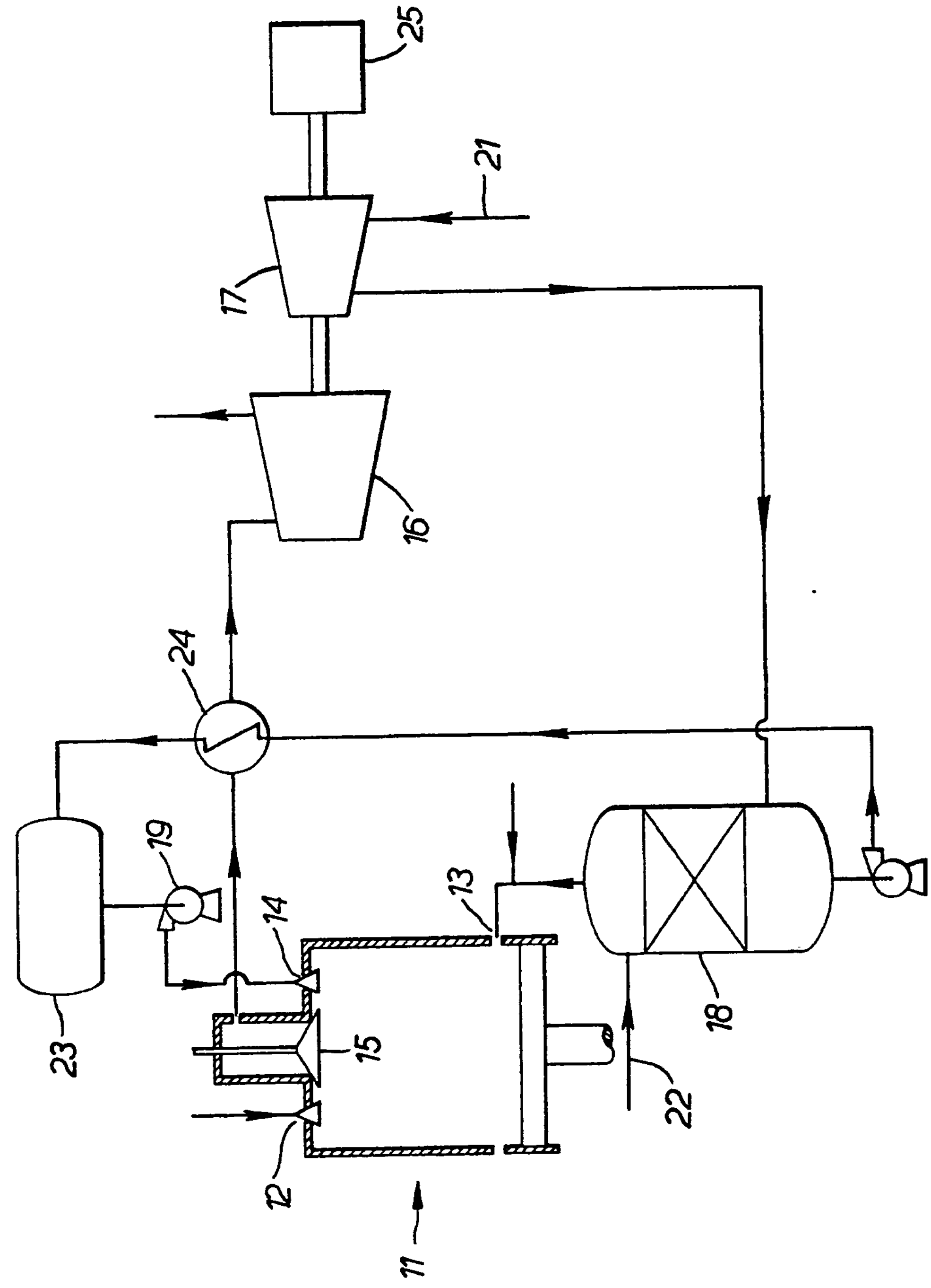

SPECIFICATION

Engines

The present invention relates to engines for burning fossil fuels to convert the heat energy produced into mechanical energy or power. The invention is particularly applicable to internal combustion engines such as the two-stroke, uniflow scaveninging type engines or any four stroke engine designs and has for one of its objects to increase the motive power produced by burning the fuel.

For the purposes of the present application the engines to which the invention relates will be referred to as internal combustion engines, though it is most applicable to reciprocating internal combustion engines.

Considering the case of a diesel engine, it is known that the thermal efficiency is related to the maximum pressure at which combustion occurs. Generally, the higher the combustion pressure, the higher the mean effective pressure during the expansion stroke which in conjunction with longer stroke lengths, results in more work being effected by the engine per stroke and hence, better thermal efficiency of the engine.

It is consequently an objective of engine designers to increase the combustion pressure which has resulted in the more recent large slow-speed diesel engines, proposed for marine propulsion and land base power stations, having the potential to accommodate combustion pressures in the order of 120 bars. To achieve this, high compression ratios and/or higher inlet air pressures to the diesel engine cylinder itself are required which, in turn, may be achieved by means of a combination of increasing the piston stroke length and the provision of more effective air turbo-blowers.

These developments have resulted in higher temperatures being produced at the end of the air compression stroke than are required to initiate combustion of most hydrocarbon based fuels. Also, due to the higher temperatures resulting from combustion at these high pressures, greater stresses and more severe corrosion conditions are imposed on the mechanical components of the engine which has created a need for either more durable components or improved cooling to compensate for these effects. A further disadvantage arising from the higher temperatures is the exposure of hydrocarbon-based lubricating oils to thermal cracking conditions, so increasing the tendency for the lubricating oils to degrade and causing deposition of solids within the equipment with a consequential reduction in performance.

It is well known that combustion in a diesel engine is initiated at temperatures between 360 to 450°C and that these temperatures can normally be achieved by means of air compression ratios between 20:1 and 30:1.

It is known that at about 500°C practically every hydrocarbon fuel will in fact combust, due to a series of complex cracking and oxidising reactions, and it is generally recognised that it is not normally necessary to exceed this temperature to initiate combustion by means of compression of the air with most liquid hydrocarbon fuels and even mixtures of liquid and solid fuels such as oil/coal mixtures. However, this temperature is normally exceeded when compression ratios exceed about 35:1 when the suction air temperature is at ambient and in fact at compression ratios of 50:1, temperatures in excess of 500°C can result where compression is adiabatic.

It is also well known that in addition to contributing to complete combustion, excess air in the cylinder has a heat diluent effect and in fact helps to keep the working temperatures of the various engine components within acceptable limits, especially the piston, exhaust valves and lubricating fluids. However, the energy expended in compressing that portion of air which is in excess of the stoiciometric quantity required for complete combustion of the fuel represents an irreversible thermodynamic loss.

It is a further object of the invention to overcome the problems associated with such high temperatures and to enable higher combustion pressures to be achieved without increasing the excess air ratio and the corresponding irreversible thermodynamic losses.

According to the invention, there is provided a method of operating an internal combustion engine having a compression stage, an ignition stage and a combustion/expansion stage, in which water is introduced to the engine during the compression stage and during the combustion/expansion stage, while preferably no water is introduced at the ignition stage, and in which the excess air admitted to the engine, over and above that required stoichiometrically for combustion, is reduced by an amount such that the heat diluent effect of the reduced amount of excess air is compensated for by the amount of water introduced in particular by its evaporative effect. The engine is preferably a reciprocating internal combustion engine, particularly a diesel type engine.

Preferably, the exhaust gas is used in a manner known per se to drive a tubro-expander which in turn drives a compressor which compresses air supplied to the engine as well as possibly an electrical power generator. The air may be compressed to a pressure above 2 bar.

According to another aspect of the invention there is provided an internal combustion engine system comprising an engine having a compression stage, an ignition stage and a combustion/expansion stage, and further comprising means for introducing water to the compression stage and the combustion/ex-

pansion stage, but preferably without means for introducing water at the ignition stage.

The irreversible losses attributable to excess air compression may be considerably reduced by injecting a substantial amount of water directly into the combustion chamber. This may be achieved by means of a water spray nozzle, injection taking place during the compression stroke, preferably towards the end of the compression stroke. Upon evaporation, the water limits the final compression temperature. It has been found that this final compression temperature may be limited to between 400 and 550°C at the completion of the air compression stroke by injecting the appropriate quantity of water and that the quantity of excess air can be reduced by a corresponding amount i.e. so that the heat diluent effect of the reduced amount of excess air is compensated for by the amount of injected water during the subsequent combustion stage.

When fuel is injected into the cylinder and starts to burn, there is a rapid rise in both temperature and pressure. The amount of excess air would normally have been adjusted so that the maximum tolerable combustion temperatures in conjunction with maximum pressure of the engine could not be exceeded, the controlling limitation being due to a combination of effects such as stresses on the engine components, excessive wear or burning of particular component parts or degradation of the lubricants primarily due to thermal cracking. By injecting further water directly into the combustion chamber immediately after the initiation of the combustion reactions in sufficient quantity and at controlled rates to limit the maximum temperature in the combustion chamber to a tolerable level without unduly restricting the reaction rates of the combustion process, an even lower proportion of excess air is required.

Thus by injecting water in the form of a spray both during the compression and combustion strokes of the engine in the appropriate proportions such that the temperature limits of the engine are not exceeded yet are adequate to effect complete combustion, a significantly lower proportion of excess air is required. This results in a consequential reduction in irreversible energy losses associated with the compression of excess air and also reduces the thermal stresses imposed on the engine components. There is also a further benefit in that there is a reduced tendency towards thermal cracking of the lubricating fluid especially that used in high temperature coolant services such as within the piston head itself.

Further, by the use of the present invention, considerably higher combustion pressures may be accommodated compared to the present known limits, e.g. pressures even in excess of 200 bar, which has the beneficial effect of even further increasing the thermal efficiency of the system.

Preferably, during the air compression stroke the amount of water injected into the combustion chamber represents 1.5 to 2.5 times the weight of the fuel and the amount of water introduced into the combustion chamber immediately after combustion has been initiated represents 2.5 to 3.5 times the weight of the fuel.

Preferably, the water is introduced in quantities 3 to 6 times greater, measured by weight, than the quantity of fuel injected into the engine.

Preferably, 30 to 50% of the total injected water is introduced into the engine during and towards the completion of the compression stage with the balance being injected during the combustion/expansion stage, soon after combustion has been initiated. The amount of excess air expressed as a ratio of the minimum stoiciometric quantity is preferably reduced from a typical ratio of 2.5:1 to 1.5:1, which may result in an overall thermal efficiency improvement of around 6% at a combustion pressure of 120 bar. It has been further found that by reducing the excess air ratio to 1.5 to one and operating the combustion chamber at 200 bar, the thermal efficiency may be further improved by around 2%.

Another benefit of this technique is that due to the reduced proportion of inlet air per unit of fuel combusted a higher power output may be achieved for the same combustion chamber diameter and engine speed, the potential increase in power output being approximately proportional to the increased quantity of fuel that may be burnt in the engine, namely in the order of from 20 to 50%, which can result in a substantial saving in capital investment for a given power requirement. A further benefit is that by having the facility to limit independently both the maximum compression and combustion temperatures by varying the relative proportion of injected water some control may be exercised over the rates of the combustion reactions including side reactions such as the formation of noxious gases, in particular the oxides of nitrogen which are encouraged by high peak temperatures.

It is known that by indirect cooling of the air previously compressed in a turbo-charger before induction into a diesel engine, the mass of air introduced can be increased, which in turn increases the potention power output for a given cylinder diameter, while the resultant temperature after the main compression stroke is lower than it would be without previous cooling. The heat removed by this means of cooling, however, is normally either rejected from the system or recovered for other heating purposes, but is nonetheless regarded as an energy loss in the context of fuel energy conversion to power. It is also known that heat may be recovered from diesel

engine exhaust gases, which would normally have a temperature around 300 °C, by indirect heat exchange for example in the generation of steam. However, unless such steam is expanded to perform useful work in for example a steam turbine it is normally again considered as an energy loss in the context of fuel energy conversion to power.

Preferably the water injected to the combustion chamber is preheated to as high a temperature as is practically possible. This is preferably achieved by either direct or indirect heat exchange with the previously compressed air prior to its introduction into the combustion chamber and also preferably subsequently by means of a second stage of indirect heat exchange with the hot exhaust gases from the engine. Thus, the recovered heat may in fact be returned to the engine and beneficially used. It has been found that by preheating the water in this way, the total quantity of water that may be injected into the engine, and which subsequently evaporates into steam to do useful work, may be increased by around 20% which may improve the overall thermal efficiency of the system by a further 2%.

It is well known that the overall efficiency of a diesel engine is improved by provision of turbo-chargers. These rotary machines take energy from the exhaust gases and use this to boost the pressure of the atmospheric air, hence increasing the mass per unit volume of air entering the engine. Such turbo-chargers are usually mounted on the engine body itself although this is not mandatory.

It is well known that the thermal efficiency of expansion turbines, whether steam or gas, is a function of the mass flow rate and the temperature drop across the machine as well as the expansion ratio and other mechanical design features. Many designers in fact use as a rough guide the temperature drop of the working fluid which passes through the machine as a preliminary basis for assessing the potential work done by a machine and hence its efficiency. It is generally accepted that, for a given machine design, an increase in mass flow through such an expansion machine results in an increase in generated power, independently of the inlet temperature for a given expansion ratio.

By separately injecting water into the engine in accordance with the invention, the molal ratio of exhaust gases to inlet air is increased, typically from 1.02 to 1.35 for a water injection rate of 4.5 times the fuel injection rate, and the mass ratio is similarly increased. It has been found therefore that by injecting this water into the engine, the resultant exhaust gases increase the nett recoverable power from a subsequent gas-steam expansion turbine. If this is used to drive an air compressor providing inlet air to the engine, greater compression of the air to the engine can be achieved with a consequential increase in the engine capacity and small improvement in thermal efficiency of the overall energy system.

It is well known that when air enriched with oxygen is combusted, the resultant temperature is higher than with non-enriched air.

It has been found that when enriched air is supplied to an engine, thereby reducing the volume of air required for combustion, in conjunction with direct injection of hot water into the engine, in accordance with the invention, in quantities of 4 to 5 times the amount of fuel injected, to limit the maximum temperature within tolerable limits, the overall thermal efficiency of the system and the potential power output for a given cylinder diameter and speed may be further increased. When air is enriched with oxygen to increase the oxygen proportion by 50% and the total amount of excess oxygen is decreased from a typical excess amount of 2.5:1 to 1.5:1, the overall thermal efficiency of the system as described can be increased by around 12%.

In summary, by means of a combination of heat exchanging injection of water against warm air from initial air compression by means of a turbo-blower and against exhaust heat from the exhaust gases from an internal combustion engine and injecting the heated water directly into the engine both during the air compression stroke and subsequent expansion strokes after the initiation of combustion and by reducing by a corresponding amount the proportion of excess air such that the machine now becomes in effect a steam-diesel engine in conjunction with a steam-gas expansion turbine and with minor modifications to the combustion volume, the overall thermal efficiency of the system as referred to the proportion of combustion heat converted into motive power can be significantly increased.

It has been found using a combination of these techniques that the overall thermal efficiency may be increased from between 7 to 12 percent thereby realising substantial savings in the primary fuel consumed by the energy conversion system as well as increasing the potential power output for a given engine cylinder diameter and engine speed.

It should be noted, there seems to be little, if any, benefit in simply injecting water without a corresponding reduction in the quantity of excess air.

The invention may be carried into practice in various ways and one embodiment will now be described by way of example with reference to the accompanying drawing in which the single figure is a schematic diagram of a steam-diesel engine system in accordance with the invention.

The apparatus comprises a diesel engine (represented diagrammatically by a piston and cylinder arrangement) 11, having a fuel inlet valve 12, an air inlet valve 13, a water inlet

valve 14 and an exhaust valve 15. The apparatus further includes an exhaust gas expansion turbine 16, an air turbo-compressor 17 driven by the turbine 16, a packed column 18 for gas liquid contact and a water injection pump 19.

In use air 21 at a substantially lower excess air ratio than that normally used is initially compressed from atmospheric pressure to about 2.0 bars in the compressor 17, driven by the turbine 16, which results in an air temperature rise of around 120C°. Although this may normally be achieved by one stage of compression, two stages may be employed resulting in a higher discharge pressure and a correspondingly higher discharge temperature rise.

The air is then cooled in the column 18 by direct counter current contact against an inlet stream of clean water 22. Sufficient clean water is introduced so that the cooled air leaving is saturated with water, and is at a temperature between 20 and 50°C. The air then passes to the air inlet valve 13 of the engine 11, and the water to a surge drum 23 (after indirect heat exchange, with the engine exhaust).

During the air compression stroke hot water at a temperature preferably higher than 200°C and even more preferably higher than 275°C is injected from the surge drum 23 through a spray nozzle at the water inlet valve 14 at a controlled rate by means of the injection pump 19 so that the temperature of the air being compressed is never below its water dew point and so that the eventual temperature at the end of air compression is between about 400 and 500°C, or at any rate, sufficiently marginally higher so that when fuel is injected into the combustion chamber through a separate spray nozzle at the fuel inlet valve 12, self ignition occurs. Injection of water is stopped before the fuel is injected into the combustion chamber so that there is no "free" water in direct contact with the fuel prior to the initiation of combustion since this may delay ignition.

Immediately after ignition of the fuel, water is again injected through the same water injection nozzle, possibly at a higher controlled rate, depending on the desired effect in respect of modulating the rate of combustion so that the maximum tolerable temperature of the particular engine or lubricating fluid is not exceeded during the combustion stroke. Towards the completion of the combustion stroke in the case of a two-stroke engine with an overhead exhaust valve 15 as indicated, the exhaust valve 15 opens and the steam/-combustion gas mixture is exhausted from the engine cylinder. This is indirectly heat exchanged in a heat exchanger 24 against the water prior to its entering the surge drum 23. The heated injection water may be at a pressure as high as 85 bars if a temperature of 300°C after heat exchange as it is passed to the surge drum 23.

After the heat exchanger 24, the exhaust gas from the engine cylinder, is passed to the expansion turbine 16, the inlet temperature being between 250 and 150°C, The power generated in this turbine 16 which is in excess of that necessary to drive the air compressor 17 may be used to drive an electric generator 25 or some other machine. Normally with this system the excess turbo-power will be in the order of 15% of that required by the compressor 17.

Alternatively, the exhaust gases may be divided such that a portion is used to drive separately a turbo-air compressor with its dedicated expansion turbine and the balance used to drive an electric generator with its own dedicated expansion turbine.

Subject to the water dew point of the gases leaving the expansion turbine being lower than the expansion turbine exit temperature, a portion of the water from the surge drum 23 may be injected into the turbine inlet to increase the mass flow. The water dew point temperature of the exit steam-gases should normally be about 70°C at atmospheric pressure.

CLAIMS

1. A method of operating an internal combustion engine having a compression stage, an ignition stage, and a combustion/expansion stage, in which water is introduced to the engine during the compression stage and during the combustion/expansion stage, and in which the excess air admitted to the engine, over and above that required stoichiometrically for combustion, is reduced by an amount such that the heat diluent effect of the reduced amount of excess air is compensated for by the amount of water introduced.

2. A method as claimed in Claim 1 in which substantially no water is introduced at the ignition stage.

3. A method as claimed in Claim 1 or Claim 2 in which the exhaust gas is used to drive a turbo-expander which in turn drives a compressor which compresses air supplied to the engine.

4. A method as claimed in any preceding claim in which the inlet air is compressed by the compresor to a pressure higher than 2.0 bar.

5. A method as claimed in any preceding claim in which, prior to its introduction to the engine, the water is heat exchanged against the exhaust gas.

6. A method as claimed in Claim 5 in which, prior to its heat exchange against the exhaust gas, the water is heat exchanged against the air from the air compressor.

7. A method as claimed in any preceding claim in which the water is heated within the range of 150 to 300°C before being injected

into the engine.

8. A method as claimed in any preceding claim in which the water is introduced in quantities 3 to 6 times greater, measured by weight, than the quantity of fuel injected into the engine.

9. A method as claimed in any preceding claim in which 30 to 50 per cent of the total injected water is introduced into the engine during and towards the completion of the compression stage with the balance being injected during the combustion/expansion stage, soon after combustion has been initiated.

10. A method of operating an internal combustion engine substantially as herein specifically described with reference to and as shown in the accompanying drawing.

11. An internal combustion engine system comprising an engine having a compression stage, an ignition stage and a combustion/expansion stage, and further comprising means for introducing water to the compression stage and the combustion/expansion stage.

12. A system as claimed in Claim 11 without means for introducing water at the ignition stage.

13. A system as claimed in Claim 12 further including a turbo-expander operated by exhaust gas from the engine and connected to a compressor for compressing the air to the engine.

14. A system as claimed in Claim 13 further including heat exchange means between the water and the exhaust gas from the engine and heat exchange means between the water and the compressed air.

15. A system as claimed in any of Claims 12 to 14 including a surge drum for the water.

16. A system as claimed in Claim 15 including a water pump for supplying the water from the surge drum fto an injector means to the engine.

17. A system as claimed in any of Claims 14 to 16 in which the heat exchange means between the water and the exhaust gas comprises a gas/liquid contacting packed column.

18. An internal combustion engine system constructed and arranged substantially as herein specifically described with reference to and as shown in the accompanying drawing.

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